Attachment E

Technical Support Document

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I. Background

The pollutants of interest from the large spark-ignition (LSI) category of engines are oxides of nitrogen (NOx, mostly NO and NO_2), non methane hydrocarbons (NMHCs, for the purposes of this document the same as hydrocarbons or HCs), and carbon monoxide (CO). The theory of formation of these pollutants is fairly well understood, mostly as a result of decades of research on automotive emissions. An underlying premise of the LSI regulatory effort is that such automotive knowledge and technology is readily transferred to engines in the LSI category.

A. Existing Engine Design Characteristics

The LSI engine category consists exclusively of four-stroke cycle engines, but it encompasses a wide variety of engine characteristics. The power ranges from more than 25 horsepower to several hundred. Displacements range from about one liter to more than seven liters. However, two of the most significant distinguishing characteristics are cooling medium and fuel.

1. Water-Cooled

Water-cooled engines utilize a water jacket surrounding the cylinder and other vital engine locations to circulate coolant (usually a water and antifreeze mixture) for the removal of excess heat of combustion from those locations. The coolant is circulated through the engine via an engine-driven pump, and is then routed to a radiator where the heat is transferred to the ambient air. The coolant is then routed back into the water jacket where it picks up more heat to repeat the process.

One advantage of water cooling relative to air cooling is the ability to maintain more spatially uniform and constant temperatures in critical engine locations. This allows tighter clearances between moving parts without danger of seizing or otherwise damaging the engine. Tighter piston-to-cylinder wall clearances provide better oil control to reduce oil consumption, and better combustion gas sealing for reduced oil contamination and higher engine efficiency (better sealing and oil control also lead to reduced HC emissions). Water cooling also allows placing the engine in more confined locations with the radiator openly located in a more remote location for exposure to cooling air.

Disadvantages of water cooling primarily consist of the excess weight, complexity and maintenance involved. Radiators and coolant pumps add significantly to the cost and weight of the engine package and are vulnerable to damage and subject to corrosion if not properly maintained. Coolant hoses between engine and radiator are also subject to deterioration and damage with subsequent catastrophic loss of coolant. Internal engine coolant leaks through faulty or damaged gaskets can contaminate engine oil or hydraulically lock up an engine, causing major damage.

2. Air-Cooled

In principle, air cooling results in a much simpler and more robust engine design than water cooling. High temperature engine parts, such as cylinder heads and cylinders, are manufactured with large external fins that serve to increase the surface area for transfer of heat to the surrounding air. Air is forced past and over these fins, either by use of a fan powered by the engine or simply through the motion of the vehicle through the surrounding air. Shrouding is often used to further guide and control the air flow over critical engine surfaces.

Advantages of air cooling over water cooling include the reduced cost and complexity due to the lack of a radiator, cooling jackets, coolant hoses, etc. Air cooled engines are less sensitive to the sort of damage that would cause a coolant leak in water-cooled engines. Finally, air cooled engines can dispense with the maintenance required to maintain a liquid cooling system, such as radiator flushing and coolant changes.

The primary disadvantage of air cooling is the difficulty in maintaining uniform temperatures of critical components, with the resulting design and manufacturing compromises that must be made. For example, without uniform temperature control around the entire circumference of an engine cylinder, thermal expansion of the piston and cylinder and the resultant piston-to-cylinder clearances will not be uniform. This can result in oil control problems and high combustion gas blowby, or even engine seizure. Non-uniform temperatures can also be the cause of head gasket leakage and failure.

Other disadvantages include the need for an open engine location for adequate air flow, the need to keep the engine driven fan and shrouding clean and free of obstructions, and the sensitivity of engine temperature to ambient temperature conditions. (Ambient temperature sensitivity for liquid-cooled engines is greatly reduced through the use of a thermostat to modulate coolant flow through the radiator.) Most importantly for emission control purposes, especially for older engine designs, an excessively rich fuel mixture is often used to keep combustion chamber temperatures low enough to avoid negatively impacting engine life. This is particularly true in terms of valve and piston life. However, this problem can probably be overcome through the use of more modern combustion chamber materials and design techniques.

3. Valve Placement

Some older engine designs utilize side valves (often called flathead, valve-in-block or L-head engines) as compared to more modern overhead valve (OHV) designs. Side valve designs have several advantages, including simplified valve trains (no pushrods and rocker arms or complex overhead cam mechanisms), simplified cylinder heads (no moving parts in the head, no critical head cooling requirements, etc.) and so forth. Side valve designs also have severe drawbacks such as locating the hot exhaust port immediately next to the cylinder (with the accompanying thermal distortion to the cylinder), long burn times (with related combustion stability problems), larger combustion chamber surface area (with greater heat transfer losses and larger quench area), reduced volumetric efficiency, etc. Many of these factors combine to cause side valve engines to have inherently high emission levels, particularly for HCs.

Because of the performance advantages of overhead valve designs, they have dominated most areas of the internal combustion engine market for several decades. However, side valve engines still exist in the smaller engine arena because of their low cost of manufacture and the previous lack of concern about their relatively limited performance and higher emissions (i.e., there has been little incentive to update their design). Nevertheless, based on current testing (see discussion of Engine E tests results in Section III, below) staff believes there are no insurmountable technical problems involved in significantly reducing emissions from side valve engines to meet these regulations.

4. Fuel

The primary fuels used for LSI engines are liquefied petroleum gas (LPG, consisting mostly of propane with some propene, butane and other trace HCs) and gasoline. A small number are fueled by compressed natural gas (CNG, consisting mostly of methane), and some have a dual fuel (operator switchable between gasoline or LPG) capability.

LPG and, to a much smaller extent, CNG, are used largely for indoor operation of fork lifts and similar equipment, due to their tendency to form significantly lower levels of CO than gasoline operation. The California Department of Industrial Relations (DIR), as part of the California Occupational Safety and Health program (CalOSHA) has set standards and regulations for the maximum allowable indoor levels of worker exposure for CO and NO_2, as well as maximum engine tailpipe exhaust CO concentration standards (see discussion below). Many indoor equipment operators use LPG fuel to address these CO requirements and concerns. Approximately 80 percent of all engine-powered forklifts sold are LPG-fueled.

Other advantages of LPG include: easier and safer storage than gasoline due to the use of robust, sealed containers and due to its dissipative gaseous nature; the storage pressure of about 120 to 170 psi makes the containers easy to fill at any one of numerous locations, relative to CNG; it generally has a higher octane rating than gasoline (though LSI engines are seldom designed to utilize the higher octane); and it has the potential for lower lifetime fuel costs than gasoline. In addition, LPG and its combustion products have much lower ozone-producing reactivity than gasoline and its products. Finally, in many areas, fueling services can be hired which deliver LPG fuel tanks to the user's site, and remove the empties, with large potential savings since the need for on-site bulk storage and vehicle tank filling facilities is removed.

Disadvantages of LPG as a vehicle fuel include significant time-to-time and location-to-location variations in fuel composition. Such non-standardized fuel composition makes it difficult for engine manufacturers to optimize designs for engine and emission control capability and durability. In an effort to address this problem, California regulations currently require that the propene content of LPG to be used as a motor fuel should be limited to 10% maximum, with a further reduction to 5% in January 1999. (Excess propene content is known to reduce the octane rating of the fuel and is suspected of increasing gum deposits on engine and fuel system components. Related test programs are currently underway to investigate and quantify such effects on engine and emissions performance.) Limits on other constituents such as water are also included. These regulations are a significant step toward addressing the LPG fuel composition issue in California. Unfortunately, similar restrictions on LPG fuel content do not exist in states outside California, which could force manufacturers to either design separate California and 49-state engine models, or forego many of the benefits of California's fuel composition requirements.

Other disadvantages of LPG include poor cold weather operational characteristics, weight of fuel cylinders during replacement/refueling operations, and poor intake valve and combustion chamber cooling capability.

As mentioned, CNG-fueled engines and vehicles have lower CO forming potential than gasoline, and since the fuel and the exhaust hydrocarbons are mostly methane, the ozone forming reactivity is extremely low. However, CNG requires high pressures (about 3,000 psi) to obtain reasonable volumetric energy density. These pressures in turn require expensive high pressure storage tanks, high pressure compressor fueling facilities, and high pressure plumbing and regulators on the engine and vehicle. Also, the relatively small amount of CNG contained in onboard fuel tanks leads to short vehicle run times between refueling, with consequent impact on productivity. For these and other reasons, CNG has not made significant inroads into the LSI market and will not be further addressed in this document.

Gasoline, primarily because of its wide availability and familiarity in automotive use, is widely used as a fuel in the LSI category. It's advantages include ready fuel availability, high energy density, and ready use of commonly available engine and fuel-delivery components. Disadvantages of gasoline include its high flammability, its spillable liquid form (doesn't dissipate from a leak as readily as the gaseous fuels), the toxic nature of some of its components (e.g., benzene), and the high photochemical reactivity of gasoline vapors and exhaust products. In addition, much attention is currently being paid to contamination of groundwater from leaking underground storage tanks (USTs), with many owners of such tanks being required to dig them up and replace them with more leak-resistant facilities at significant expense. Many users of LSI equipment see LPG as a way of avoiding the UST problem and liability.

The typical dual-fueled vehicle is capable of switching between operation on gasoline and LPG upon operator demand. This capability is quite advantageous in cold weather applications as the engine can be started and warmed on gasoline, and then switched to LPG when the engine is sufficiently warmed. Dual-fueled engines are also desirable in the rental market, when one renter prefers gasoline operation and the next renter wants to run on LPG.

B. Fuel Delivery

Depending on the fuel, the fuel delivery system on the engine or vehicle can be quite complex.

1. Gasoline Systems

Typically, gasoline engines use simple float-type carburetors with fuel storage tanks made of sheet metal or plastic. These systems have the advantages of being simple and robust, and cheap to manufacture and maintain. By far, the large majority of these systems utilize an open-loop control approach, with the carburetor relying on the manufacturer's calibration to function sufficiently well over a wide variety of operating conditions.

Unfortunately, simple carburetion cannot adequately control the typical engine's fuel-air ratio for proper emissions control, especially when coupled with three-way catalytic (TWC) converters. Carburetors also have the tendency to lose their calibration, with mixture ratios becoming progressively richer as the moving and metering parts of the carburetor wear. Some forklift manufacturers have developed closed-loop control systems, some with carburetors and some with automotive-style fuel injection, but only for use in special applications where CO and other pollutant emissions must be held to an absolute minimum. These manufacturers report that the market demand for such systems has been quite small (on the order of one or two per year), and that there is a significant purchase price premium associated with them due to this exceedingly low production volume.

2. LPG Systems

LPG use requires a pressure storage vessel, a pressure regulator, a heat exchanger (using engine coolant as the heat source) and some sort of fuel-air mixer. LPG is typically stored at about 130 to 170 psi, where it remains liquid at normal ambient temperatures. Maintaining a liquid state for storage provides volumetric energy density roughly comparable to that of gasoline. The pressure regulator and heat exchanger combine to change the liquid LPG to a vapor at the desired pressure and temperature for use in the engine.

The mixer typically consists of a diaphragm, exposed to the engine intake air stream, attached to a needle and orifice assembly. The diaphragm responds to changes in engine intake vacuum (which in turn is controlled by engine load and throttle setting), raising and lowering the needle to finely adjust the amount of LPG that is admitted to and mixed with the engine intake air.

Again, such an open-loop system is inadequate for precise fuel-air ratio control. Therefore, some component manufacturers, such as Impco and Engine Control Systems Ltd., have developed closed-loop systems which utilize an oxygen sensor and computer to modulate the vacuum applied to the diaphragm and thus more precisely control the mixture ratio. However, there are some indications that these systems can have a slow transient response and can negatively impact the operability characteristics of the engine. Some attempts have been made to utilize gaseous fuel injectors in closed-loop systems, which could significantly reduce any operability problems. At present, such injectors are expensive due primarily to their low production volumes, but the costs could be reduced with sufficient demand in a way analogous to the changeover of on-road vehicles from carburetors to fuel injection.

C. Governors

To modify an engine's torque and horsepower vs. speed curves to fit a particular application, manufacturers typically resort to the use of some type of governor. Governors are also used to derate an engine to a lower power level, typically by limiting the engine's top speed. Finally, in many applications, a governor is used to maintain a set engine speed in operation, regardless of changes in the engine's load.

There are three main types of governor: mechanical (usually based on the centrifugal effects of rotating weights driven by the engine crankshaft), pneumatic, and electronic. Electronic governors are the most sophisticated and are readily incorporated in electronic engine controls used with closed-loop fuel systems. In fact, for engines already utilizing such electronic fuel delivery systems, electronic governor use requires less hardware than other governor systems and can therefore result in a cost savings to the manufacturer.

A major issue surrounding the subject of governors results from their modifications to engine power and torque curves. Since most test cycles define key parameters in terms of rated power, torque and speed, or percentages of those quantities, the same engine with different types of governor or governor settings could require many different sets of certification tests and applications. This subject is discussed further in the test cycle section, below.

D. Electric Vehicles and Equipment

Many types of equipment that are included in the LSI category when powered by gasoline or LPG engines are also available in electrically-powered versions. Such electrically-powered equipment in operation has zero levels for emissions of any of the pollutants of concern. Most such equipment is used in indoor materials handling applications, such as electric forklifts for indoor applications where CO emissions must be absolutely minimized (warehouse type building supply stores are good examples.) Electric forklifts are available from several forklift manufacturers, such as Toyota, Nissan, Clark, Crown, and others. As another example, Taylor-Dunn Manufacturing Company makes and sells burden carriers and utility vehicles to the U.S. Postal Service, among other customers. And because of air quality concerns, many airlines utilize electric ground support equipment (for luggage handling, etc.) at various airports.

Electrically-powered vehicles and equipment utilize large battery packs, typically of deep discharge lead-acid design, to provide the power for equipment operation. The batteries must be recharged periodically and, unless of the maintenance free variety, water levels need to be monitored and maintained. Charging facilities must also be provided with proper ventilation to avoid explosive hydrogen gas buildup. Battery packs can weigh as much as one to three thousand pounds depending on application, and require special equipment for handling. (Usually a major problem in vehicular applications, such heavy weights can actually be advantageous for equipment like counterbalanced forklifts.) For most working applications, battery packs generally are sized to allow operation for a complete 8 hour shift on one charge. Endurance in some applications may be less, depending on duty cycle and other factors.

Upon battery exhaustion, and depending on the equipment and its design, the equipment can either be removed from service during the recharge period or the battery pack can be exchanged for a fully-charged pack. In this way, the equipment can be kept operating continually, in use with one battery pack while another is being charged back to full capacity. Proper design minimizes the exchange process time to just a few minutes, utilizing quick-disconnect electrical connectors and sliding/rolling battery holders and other specialized accessories. Battery pack costs can amount to about 10 percent to 15 percent of the total equipment cost, and most operators obtain at least one additional pack to allow multi-shift operation.

The Electric Power Research Institute (EPRI) is currently developing a fast charger system that can greatly reduce the time required for battery charging. For example, the typical forklift battery pack requires approximately 8 hours to recharge with conventional chargers. The new EPRI fast charger can bring the same pack to full charge in about one half hour, though it would periodically require a one to two hour equalization charge. The projected cost of the fast charger is about $25,000, but for a large enough fleet this could be more than offset by reduction of the need to procure extra battery packs to extend vehicle operation time.

A major advantage of electrically-powered equipment is that they typically require far less maintenance than comparable LSI powered equipment since they do not require oil changes, spark plug replacement, etc. In addition, electric equipment powertrain components are inherently more reliable, and fuel costs are drastically reduced. Based on conversations with Sacramento-area forklift dealers, these factors generally result in reduced total life cycle costs. Electric equipment is also invariably quieter than its engine powered counterpart.

Disadvantages of electric-powered equipment include reduced work capacity. For example, most electric forklift manufacturers only make their products available with up to about a 6,000 pound lift capacity, while engine powered models with capacities of 3 times that or more are available. Electric equipment also is usually slower, has slower lift speeds and does not operate as well on steep ramps and slopes. However, further development work continues to extend the capabilities of electrically-powered industrial equipment.

Population data for 1995 indicate that there were over 41,000 ride-on type electric-powered forklifts in operation in California in that year. At the same time there were over 50,000 gasoline- and LPG-fueled forklifts in use in the state. This information indicates that electric forklifts are commonly accepted as having adequate performance, and that a significant portion of the state's forklift population can already be considered zero-emission, greatly reducing the impact of this category of equipment on air quality.

E. Cal/OSHA

The Federal Occupational Safety and Health Act of 1970 contains provisions allowing California to administer its own workplace safety and health program. As previously noted, California's program is called CalOSHA and is administered by the state's Department of Industrial Relations (DIR). Of particular interest are the requirements and regulations CalOSHA has established to safeguard workers from harmful exposure to engine exhaust and its components. A primary regulation of concern regards worker exposure to several airborne contaminants, including such exhaust emission components as CO and NO_2 (Title 8, California Code of Regulations, §5155). CalOSHA also has standards placing limits on engine exhaust emission concentrations of CO, and the test procedure to be used for CO measurement (Title 8, California Code of Regulations, §5146).

Please note that the CalOSHA standards are intended to provide protection to workers from harmful exhaust substances in the immediate work environment. In contrast, the proposed ARB regulations are aimed at the control of air quality for the general public over large urban areas significantly beyond the immediate source of the emissions. These different goals necessitate some differences in regulatory design and implementation. For example, ARB typically requires routine testing of new engine designs and in-use engines to demonstrate whether they meet regulatory requirements. In contrast, DIR procedure is to require engine testing for CO emissions beyond their standards only when there is other evidence of a problem, such as excessive ambient CO levels in a facility operating the engine in question.

Staff has discussed the proposed LSI regulations with DIR personnel in order to coordinate and avoid conflicts with existing CalOSHA requirements. At present, ARB staff and DIR staff agree that no conflict exists and that, in fact, the ARB regulations should significantly reduce worker exposure to harmful exhaust emissions.

F. Underwriters Laboratories

Underwriters Laboratories is a not-for-profit corporation whose reputation for certifying the safety of machinery, equipment and consumer products is known worldwide. UL certification of a product signifies that it has been tested and determined to meet applicable standards intended to safeguard personnel against exposure to such hazards as electrical shock, fire, excessively high surface temperatures, etc.

Several equipment manufacturers have informed staff that their customers expect the equipment they purchase to be UL approved. These manufacturers express concern that the presence of catalytic converters could make it difficult to meet UL requirements for fire safety and safety from exposure to high temperature surfaces. They also express concern about the expense of conducting the tests required by UL.

Staff has discussed this issue with UL personnel. Catalytic converter certification would be covered under standard UL 558. According to UL, this standard is concerned with limiting the surface temperatures of vehicle or equipment components located adjacent to a muffler or catalytic converter, and also considers the converter's structural capability to contain backfire pressures, etc. This can be done directly through test of a converter as installed in the vehicle for which certification is sought.

Another way of obtaining UL approval is through a component approach. The catalytic converter manufacturer can ask for and obtain UL approval for use of a catalyst in a reference installation. The reference installation usually represents a worst case scenario in terms of engine size, converter proximity to sensitive surfaces, etc. The component approval process would then consist of testing for temperatures, capability to sustain backfire pressures, and so forth, in that reference installation. The equipment manufacturer would then need to show to UL's satisfaction that it is using that catalytic converter in an application similar to the reference installation or in an inherently safer configuration, as determined by engineering evaluation. In this way, actual converter testing for UL approval is minimized, and the costs and responsibility of obtaining such approval are shared between the equipment manufacturer and the converter manufacturer. Catalytic converter manufacturers have expressed the belief that use of a component approval process will minimize the costs of obtaining UL approval.

II. Emission Control Techniques

SIP Measures M11 and M12 provide the incentive for the LSI regulations. They assume that the application of proven automotive emission control technology, and in some cases off-the-shelf hardware, should be adequate to drastically reduce LSI emissions.

As previously noted, spark ignition engines emit three major pollutants. NOx forms in the combustion process through the combination of nitrogen and oxygen, both supplied by the intake air, under conditions of high temperature. In general, an individual engine's NOx emissions increase with increasing engine load but tend to be quite low at idle. NOx formation peaks near the stoichiometric fuel-air ratio and decreases with rich mixtures (insufficient oxygen present) and lean mixtures (decreased combustion temperatures). Designing for reduced NOx formation involves reducing the peak combustion temperatures present, reducing the time available for NOx formation, or some combination of both.

HC emissions result primarily from the incomplete combustion of fuel in the combustion chamber. In the extreme case, this results from misfire when the ignition system completely fails to ignite the fuel-air mixture near the beginning of the power stroke, and all of the unburned charge escapes to the exhaust system on the exhaust stroke. More usually, some small portion of the mixture fails to burn completely even after ignition has commenced properly. This usually results from HCs located in the piston ring clearance voids, HCs adsorbed into the engine oil film on the combustion chamber walls or adsorbed onto chamber deposits, or simply from a portion of the mixture located in the thin quench zone immediately adjacent to the chamber walls. Poor combustion quality, due to reduced bulk gas temperature and flame speed under some operating conditions (idle or excessively high exhaust gas recirculation (EGR) dilution) can also quench portions of the flame front before it has reached the combustion chamber walls. Finally, as in the case of some LSI engines, poor mixture control (or, as in the case of some older engines, deliberately rich calibration for purposes of reduced combustion temperatures) results in excessively rich mixtures where there is insufficient oxygen in the combustion chamber to oxidize all of the available HC molecules. All of these mechanisms result in HC emissions in the exhaust.

CO emissions result from the partial oxidation of hydrocarbon molecules. Instead of combining with two atoms of oxygen to create carbon dioxide (CO_2), a carbon atom is only able to combine with one atom of oxygen. High CO emissions almost always occur due to an excessively rich mixture, when insufficient oxygen is present to completely oxidize the carbon to CO_2.

The engine designer's job in reducing engine-out emissions (i.e., as emitted by the engine before aftertreatment by devices such as a catalytic converter) of all three pollutants is complicated due to the NOx-HC tradeoff. In essence, this means that the conditions that reduce one of these pollutants also result in the increase of the other. For example, high temperatures and high residence time would be ideal for more complete oxidation of hydrocarbons but they are also precisely the conditions for the formation of NOx emissions.

However, some aftertreatment devices can function without this tradeoff, the prime example being the three-way catalytic converter. This and other emission control technologies are discussed below.

A. Closed-Loop Fuel Delivery

Probably the most direct way to reduce HC emissions from LSI engines would be through the use of more precise and consistent fuel-air ratio control. Both the gasoline and LPG carburetors and mixers used on many LSI engines, especially the smaller displacements, are quite rudimentary. They are adequate in terms of allowing the engine to operate and provide power satisfactorily, but they cannot provide the constant and precise mixture ratio control needed under all operating conditions to avoid periods of excessively rich mixtures. This can result in high HC and CO emissions. Automotive-type closed-loop controls, utilizing an exhaust gas oxygen sensor and an electronic control unit (ECU) to control a special carburetor or fuel injection system, can eliminate rich mixture excursions under most operating conditions. However, due to the NOx-HC tradeoff phenomenon, controlling HC emissions by leaning excessively rich mixtures usually results in increases in NOx emissions.

As discussed below, precise mixture control is needed to maintain the near-stoichiometric mixture necessary for proper three-way catalyst operation. Indeed, in automotive use, closed-loop control is only partly an emission control end in itself, but its main purpose is to allow the major emission reductions possible with advanced catalysts.

B. Closed Crankcase

Another source of HC emissions results from the release of crankcase gases to the atmosphere. These gases result primarily from cylinder intake and combustion gases passing the piston ring assemblies into the crankcase (blowby) on the compression and power strokes. Crankcase gases also contain lubricating oil and its components, in vapor and droplet form. Reduction of crankcase emissions was one of the earliest automotive emission controls used in production. The primary approach is the use of positive crankcase ventilation (PCV). PCV requires the sealing of the crankcase from the ambient air except for a filtered air inlet, and an exit to the carburetor or intake manifold below the throttle plate. When the engine is running, manifold vacuum is applied to reduce the crankcase pressure below atmospheric, thus drawing the crankcase gases into the intake system and then into the engine combustion chambers to be burned. Fresh outside air is drawn into the crankcase through the filtered inlet.

C. Timing Retard

An early approach to NOx control involves retarding the ignition timing. Retarding the spark timing means that more of the combustion occurs later in the expansion portion of the power stroke than would have occurred if the spark was timed for peak power. This in turn results in lower burned gas temperatures and pressures and therefore lower NOx formation in the combustion chamber. Unfortunately, retarded timing also results in reduced power and reduced thermal efficiency. The impact on performance and fuel economy can be severe and places a practical limit on how much NOx reduction can be achieved through this method.

D. Exhaust Gas Recirculation

EGR involves the recycling of a small portion of the exhaust gases into the engine intake and thus into the combustion chamber. This dilution of the incoming fuel-air charge provides inert thermal mass to absorb combustion heat and thus reduce combustion chamber temperatures below maximum NOx formation levels. Proper calibration is necessary since excessive EGR leads to reduced flame speeds and therefore reduced combustion stability. The lower combustion temperatures can also lead to increased HC emissions due to reduced burnup. But, if carefully applied, EGR can provide significant NOx reductions with minimal impact on performance, fuel economy or other emissions.

E. Catalytic Converters

The catalytic converter is the primary technology responsible for the incredible improvements in automotive emission control over the past two to three decades. Indeed, due largely to the catalytic converter, ozone-forming emissions from a modern automobile are less than about 10% of the levels of an uncontrolled vehicle of the 1960s, with improved driveability and fuel economy as an added bonus. The typical modern automotive catalytic converter consists of an active catalytic material (usually one or more noble metals such as platinum, palladium or rhodium) applied as a washcoat to a substrate (usually ceramic or metal), surrounded by a mat and placed in a housing ("can") which also acts to direct the exhaust flow over the active material so as to maximize surface exposure. The two major types of converters are described below. Staff expects that three-way catalyst technology will be the approach used to meet the proposed LSI engine standards.

1. Oxidation Catalysts

The first catalysts widely used on production automobiles were oxidation catalysts, introduced in the mid-1970s. They are designed to oxidize HCs and CO to water and CO_2. They require excess oxygen in the exhaust stream, which is usually provided by an engine-driven air pump or an exhaust reed valve system.

Oxidation catalysts are not extremely sensitive to fuel-air ratio so they do not require sophisticated carburetion systems. Oxidation catalysts are not effective in reducing NOx emissions.

2. Three-Way Catalysts

Three-way catalytic converters go beyond the oxidation catalyst's capabilities by utilizing the exhaust stream HCs, CO and NOx for the simultaneous oxidation-reduction reactions that convert all three pollutants to water, CO_2, and nitrogen (N_2). The catalyst's conversion efficiency is strongly affected by the presence of excess oxygen or hydrocarbons so that tight control of the mixture ratio to maintain it near stoichiometric is essential. In more detail, the conversion efficiency can be improved if the mixture is periodically varied between slightly rich of stoichiometric and slightly lean of stoichiometric. Such intricate requirements demand a closed-loop control system.

A variation on the concept of the TWC is the dual-bed catalyst. This actually consists of two catalytic converters in series. The first conducts the reduction reactions between NOx and HCs and CO. The second is an oxidation catalyst utilizing air injection to complete the oxidation of any remaining HCs and CO. Dual catalysts do not require stoichiometric operation like TWCs, and can operate well under rich mixture ratio conditions, at the expense of increased cost and complexity.

3. Catalyst Issues

Catalytic converters for use in LSI engines will have some of the same issues associated with them as do converters used in automobiles, plus some that are unique to individual applications.

TWCs for automobiles generally cost in the range of $100 to about $300 retail for replacement units. During the recent development of ARB's small off-road engine regulations, prices of the small, low-efficiency converters for such engines were estimated to be around $25 each. For LSI applications, it is generally anticipated that use of automotive-type converters is feasible, which will help keep the costs to acceptable levels. However, it is possible that special applications could result in the need for a custom converter which could not take advantage of the high volume cost reductions associated with automotive applications. This could result in rare instances of high converter cost.

A major question that always arises during contemplation of new applications for catalytic converters is that of durability.

Converters are subject to high temperatures in normal operation (1000€F and higher), rapid temperature transients, catalyst poisons (primarily lead anti-knock fuel additives and phosphorous- and zinc-based lubricating oil additives, the latter two of which actually "mask" rather than poison the catalyst), and a potentially high vibration environment. In addition, excessive exhaust hydrocarbons for prolonged periods (e.g., resulting from persistent misfire or overly-rich mixture ratios) can lead to abnormally high catalyst temperatures. In the past, any combination of one or more of these conditions has tended to lead to catalyst deactivation or destruction, with the attendant loss of emission control. However, catalyst manufacturers have continued to research and develop better and more durable catalytic converters to overcome these problems, and much progress has been made in just the last two to three years. For instance:

> Improved ceramic substrates provide improved tolerance to long-term high temperatures and vibration, and new metallic substrates are even better than the ceramics (though somewhat more expensive);
>
> Better matting design and materials (e.g., ceramic fibers) also provide greatly improved vibration resistance;
>
> Larger washcoat pore size, in combination with calcium-based oil additives, allow masking substances to remain on the surface without hindering the gaseous diffusion of target pollutants to active catalyst sites. Therefore, modern catalysts continue to function properly with high exposure to oil additives (even high oil-consumption two stroke engines have been successfully equipped with modern catalytic converters);
>
> And, of course, the more traditional approach to poisoning problems, greater catalyst loading (essentially a bigger catalytic converter) is still available.

Many current LSI engine installations require locating the engine in a very small engine compartment, often subject to high temperatures and flammable materials. For example, many current turf care equipment designs, such as those for golf course mowers, do not have a lot of engine compartment room available for additional components. They also are subject to grass clippings that can become packed around engine components. As another example, fork lifts used in paper recycling facilities are subject to paper scraps and dust that can lodge and build up around engine components. In such cases there is the constant danger of these materials igniting upon exposure to potentially high temperature exhaust components like catalytic converters.

Because of these packaging problems, the installation of catalytic converters within a vehicle or equipment can pose special challenges. (As discussed previously, many markets demand that equipment be certified by UL as to fire hazard, especially with regard to high temperature engine components.) But staff is confident that solutions are available for most, if not all, of these packaging issues. Several catalyst manufacturers, such as Engelhard and Degussa, have become very adept at combining converters and mufflers into single units that each occupy no more volume than a conventional muffler. Thermally insulating converters reduces the potential for excessively high surface temperatures. Judicious engineering of the engine installation can provide sufficient room to locate converters away from any potential flammable materials. Finally, the use of electronic engine controls and ignition systems will greatly reduce the incidence of converter overtemperature incidents due to misfire or excessively rich mixtures.

F. Fuel Economy

Staff expects that the proposed standards can be met through the use of three-way catalytic converters and electronic engine controls, including closed-loop fuel injection and electronic ignition systems. Electronic engine controls in large part have been responsible for the great improvements in automotive fuel economy over the past two to three decades, as evidenced by both passenger car and heavy-duty vehicle improvements. Staff expects this side benefit will also be present for many emission-controlled LSI engines.

Manufacturers of gasoline-fueled LSI engines currently tend to calibrate those engines somewhat rich of stoichiometric, usually to improve transient throttle response. Rich mixture operation usually results in higher than necessary fuel consumption. As these engines age and wear, the tendency is for their mixture ratios to become even richer. Electronic engine controls would operate these engines at near-stoichiometric ratios for the duration of their useful lives, while also maintaining adequate operability. This will result not only in reduced emissions, but also in enhanced fuel economy, potentially on the order of five to 15 percent. This benefit would be maintained over the useful life of the engine.

Current LPG-fueled LSI engines are generally calibrated by their manufacturers to operate lean of stoichiometric for improved CO emissions control. Therefore the initial impact of electronically-controlled stoichiometric mixtures on the fuel economy of such engines would be to moderately increase fuel consumption. However, industry representatives have noted to us that typical practice for equipment dealers and operators is to significantly enrichen the mixture settings of new vehicles and equipment in order to improve operability. Modern electronic control systems would remove this tamper incentive by maintaining vehicle operability without excessive enrichment. This would result in fuel economy improvement over current engines as actually used in the field. Again, electronic controls would maintain the proper mixture ratio performance over the useful life of the engine, avoiding enrichment that occurs in current engines due to wear of the fuel system.

III. Actual Engine Emissions

ARB is currently sponsoring a study by Southwest Research Institute (SwRI) to develop a baseline data set for emissions from existing LSI engines and to quantify the potential for emission reductions using appropriate technologies. For the latter task, the emphasis is on automotive style TWCs with closed-loop fuel delivery. SwRI has also hosted meetings by a Technical Advisory Committee (TAC) which was charged with providing technical information and support for several key tasks during the study. The TAC consisted of representatives from several engine, equipment and component manufacturers as well as representatives from industry and ARB staff. Though the study is still ongoing, SwRI has provided ARB with an interim report. Much of the following discussion is based on information from that report.

A. Test Cycles

The test cycle used to measure an engine's emissions must be representative to an acceptable degree of how that engine is used in the field. Only then can comparisons to a common standard be meaningful, and the data be used for emissions inventory calculations. For the LSI category of engines, there are many different engine models, applications and duty cycles and it would be impossible to develop individual test cycles for all of them, or one test cycle that perfectly represents the entire category. However, it is useful to divide the LSI engine category applications into two types of duty cycle: 1) vehicular applications that operate under many different combinations of engine load and speed (e.g., forklifts, airport ground support equipment, and turf care equipment) but rarely spend much time near peak load and speed; and 2) constant speed applications that typically operate at one speed, near full load with only moderate load changes (e.g.,generator sets, irrigation pumps, and refrigeration units) .

The International Standards Organization (ISO) has developed and published the ISO 8178 standard, a set of standardized test cycles for emission testing of different types of non-road engines. Each test cycle nominally consists of an eleven mode test. A test engine is run in each mode (at a specified speed and torque) and its emission rates are measured, and then a weighting factor is applied to each mode for determining a composite emissions number. The test cycles recommended and accepted by the TAC as being most applicable are the ISO 8178-C2 cycle for vehicular applications, and ISO 8178-D2 for steady state applications. In addition, several engine manufacturers approached ARB directly about allowing the use of the ISO 8178-G1 test cycle for smaller engines used in equipment like lawn and turf care equipment, with less idle time than the other cycles account for. Table 1, below, gives the weighting factors for these three cycles (a dash indicates that base mode is not used for that particular cycle.) For the most part, each of these test cycles use those modes most appropriate to the type of application represented.

Table 1 - Weighting Factors of ISO 8178 -C2, -D2 and -G1 Test Cycles

Base Mode	1	2	3	4	5	6	7	8	9	10	11
Torque (%)	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated					Intermediate					Idle
-C2 (vehicular)	-	-	-	.06	-	.02	.05	.32	.30	.10	.15
-D2 (constant speed)	.05	.25	.30	.30	.10	-	-	-	-	-	-
-G1 (small, constant speed)	-	-	-	-	-	.09	.20	.29	.30	.07	.05

Notes: Rated speed is that speed at which the engine develops its rated power, as specified by the manufacturer.
Torque is specified as a percentage of the maximum torque available at that speed.

Intermediate speed is that speed in the range from 60% to 75% of rated speed, at which the engine develops the highest torque level.

Concern was raised by TAC members about the effects of engine governors on emissions testing using the ISO standard. For example, depending on the individual case, an engine's governor may be set such that the engine will not run at or near its ungoverned rated speed. Also, many engines are used with many different governors, which could necessitate the burdensome testing of each engine/governor combination. One member suggested that the -C2 cycle be modified to redefine rated speed as the governed speed, and intermediate speed as 50% of governed speed. Also recommended were changes to the -C2 cycle weighting factors to more closely reflect the military's standard forklift evaluation test course, MIL-STD-268C. However, none of the other TAC members were supportive of such proposed modifications.

B. Uncontrolled Emissions Levels

Five engines were donated by four different manufacturers for use in the SwRI study, on condition that results for each engine be made available to the engine's manufacturer, and that each manufacturer's confidentiality be maintained. SwRI also reviewed emissions test data from previous studies and included the appropriate results in their report. The engines range in displacement from 2.0 liters to almost 8 liters, from just under 40 horsepower to over 200 horsepower, and are typically found in forklift, industrial and other various applications, depending on the specific engine model. Table 2 presents these emission test results.

Table 2 - Uncontrolled Engine Emissions Test Data (Baseline) (g/bhp-hr)								BSFC (lbs/hp-hr)
Engine ID	Cycle	Fuel	HC	CO	NOx	HC+NOx	Remarks	
A	-C2	gasoline	1.69	20.1	12.0	13.69	Avg. of 2 tests (current project)	0.554
B	-C2	gasoline	1.49	16.3	8.3	9.79	Avg. of 2 tests (current project)	0.579
B	-C2	LPG	0.94	7.37	11.7	12.64	Avg. of 2 tests (current project)	0.526
C	-C2	gasoline	3.81	50.7	7.7	11.51	Avg. of 2 tests (current project)	0.616
C	-C2	LPG	1.70	8.80	11.5	13.2	Avg. of 2 tests (current project)	0.540
D	-C2	gasoline	3.99	124	5.4	9.39	Avg. of 2 tests (current project)	0.671
D	-D2	LPG	0.89	2.1	9.9	10.79	Avg. of 2 tests (current project)	0.455
E	-C2	gasoline	18.7	684	1.1	19.8	Avg. of 2 tests (current project)	1.43
E	-D2	gasoline	10.7	479	1.7	12.4	Avg. of 2 tests (current project)	1.10
40hp lift truck	-C2	LPG	1.17	5.74	13.8	14.97	Avg. of two tests (previous project)	n/a
F	-C2	gasoline	3.23	49.9	13.7	16.93	Avg. of 3 different carburetors (previous project)	n/a
F	-C2	LPG	2.90	141	4.93	7.83	Single test (previous project)	n/a
G	-C2	LPG	2.28	27.3	15.4	17.68	Avg. of 2 tests (fuel system x) (previous project)	n/a
G	-C2	LPG	1.88	5.32	16.73	18.61	Avg. of 2 tests (fuel system y) (previous project)	n/a
average	*both*	*both*	*3.96*	*116*	*9.56*	*13.52*	*straight, non-weighted average*	

Note: individual engines identified by letter designation only, to preserve manufacturer confidentiality

The engines which were tested under the -C2 cycle are primarily used to power forklifts or similar vehicles. Those tested under the -D2 cycle are primarily used in constant speed applications. Two engines were tested on both the -C2 and -D2 cycles since they have applications appropriate to both test cycles, and also to provide a comparison between cycles. Several engines were tested in both gasoline and LPG configurations, for comparison purposes and because they have application in both forms.

Finally, engine E shows the excessively high HC and CO emissions and low NOx emissions characteristic of an excessively rich fuel-air mixture setting (this is the classic NOx-HC tradeoff discussed previously). As shown in Table 2, engine E also had a brake specific fuel consumption (BSFC) roughly two to three times higher than the other engines had, also indicating excessively rich operation. Care must be used when including data from engine E while summarizing test results, to avoid skewing the results, and one also should keep in mind that it is a low sales volume engine.

Emission test result averages for each of the two fuels are presented in Table 3, below. This table shows that LPG fuel lives up to its reputation as a better indoor fuel in terms of reduced CO emissions. HC emissions are also lower for LPG fuel over gasoline. But for the present purposes, it is important to note that LPG shows higher NOx emissions and higher combined NOx+HC emissions than gasoline shows.

Table 3 - Test Result Averages by Fuel						
Fuel	Test Cycle	Engine ID	HC	CO	NOx	NOx + HC
gasoline	-C2	A,B,C,D,F	2.84	52.2	9.42	12.3
LPG	-C2	B,C,D, 40hp lift truck, F,G,G	1.81	32.6	12.3	14.2

Note: Engine E test results excluded

Only two engines were tested on both the -C2 and -D2 cycles (none were tested on the -G1 cycle.) The results of these tests are compared in Table 4.

Table 4 - Test Cycle Comparisons						
Test Cycle	Fuel	Engine ID	HC	CO	NOx	NOx + HC
-C2	gasoline	E	18.7	684	1.1	19.8
-D2	gasoline	E	10.7	479	1.7	12.4
-C2	gasoline	D	3.99	124	5.4	9.39
-D2	LPG	D	0.89	2.1	9.9	10.79

Comparison of the two cycles from these tests is difficult since one of them was run with engine E and its exceptionally rich operation, while the other was run with engine D but on two different fuels. But the higher level of engine E NOx emissions on the -D2 cycle vs. the -C2 cycle seems to follow from the emphasis of cycle -D2 on higher speeds and moderately higher loading (remembering that NOx generally increases as an engine becomes more highly loaded.) The difference in engine E's NOx+HC numbers also verifies that an engine's emissions are strongly related to how it is tested (which in turn is intended to reflect how an engine is used). This latter observation supports the decision to use two different cycles for LSI engine emission testing, rather than attempting to test all engines for all applications with only a single cycle.

C. Potential Effective Emission Controls

The initial emphasis in the SwRI project included the evaluation of three-way catalyst systems as an effective emission control. TWCs were a logical choice for initial investigation because of their highly successful application to automotive emissions control, and the similarity and automotive background of many LSI engines.

SwRI examined three major TWC research projects for off-road LSI engines, two from their own experience and one from a Canadian producer of TWC equipment. Two of the engines were operated on LPG, one on gasoline, and all were equipped with TWCs and the necessary closed-loop fuel controls. Compared to their previously uncontrolled configurations, the average emission reductions achieved from these engines for HC, CO and NOx were 90 percent, 97 percent and 77 percent, respectively. If one assumes that these average reductions are typical of what can be obtained for the average engine of Table 2, the potential average emission levels that can be obtained with TWC technology are shown in Table 5.

Table 5 - Potential Emission Reductions with TWC Technology

	HC	CO	NOx	NOx + HC
average of Table 1 emissions (g/bhp-hr)	3.96	115.8	9.56	13.52
typical TWC reductions (%)	90	97	77	-
estimated controlled emissions (g/bhp-hr)	0.40	3.47	2.20	2.60

Note that these controlled emission levels are significantly below the proposed standards, indicating the feasibility of those emission standards. It is apparent from this testing that TWCs can be used to achieve significant emission reductions.

SwRI was also tasked with examining options for a low-cost alternative technology or combination of such technologies not utilizing TWCs. These alternative technologies include better carburetion (open and closed-loop), EGR, ignition timing retard, exhaust system air injection, and selected combinations. Based on past experience, SwRI estimated that the best emission reductions without using a TWC could come from a combination of timing retard, mixture enleanment and improved carburetion (though still open-loop), EGR, exhaust air injection and an oxidation catalytic converter. SwRI estimated emission reductions for such a system on a typical engine would be around 80 percent for HCs and 60 percent for NOx. However, these reductions fall short of the potential achievements of a good TWC system, could have significant operability and fuel economy impacts, and could lead to a complexity and perhaps cost equal to or greater than those of the TWC system. Therefore, further development of an alternative system was not pursued during the study.

D. Three-Way Catalyst Demonstration Testing

The planning for the next phase of the SwRI project includes installation of complete catalytic converter and closed-loop fuel systems onto two engines selected from those listed in Table 2, "zero-hour" emission measurement testing, in-use durability runtime accumulation, and deterioration factor emission testing. This phase has already begun with selection of one gasoline-fueled engine and one LPG-fueled engine, and installation of appropriate systems on each.

Zero-hour emission testing has been conducted with very little accumulated time on the engine or on the added hardware, other than fuel system calibration time and catalyst degreening time. In-use runtime accumulation involves installation of each engine in an application typical of how it is commercially used, for a total of approximately 250 service hours before retesting. The difference between the pre- and post- accumulation testing results is an indication of the durability of the installed emission control equipment.

1. Engine B Zero-hour Test Results

SwRI has installed an off-the-shelf automotive catalytic converter and an Impco closed-loop mixer system onto a typical forklift engine for operation on LPG fuel. This is engine B of Table 2, which was previously baseline tested for emissions on the -C2 cycle. Approximately six test runs were made to determine the effects on emissions of adjustments to the various fuel system calibration parameters, and to optimize those parameters for minimum exhaust emissions. All testing for this engine during this phase of the project was conducted on the -C2 cycle. Table 6 shows the results of the zero-hour testing with this low-time (about 80 hours) engine, using the final set of fuel system calibration parameter values.

Table 6 - TWC Demonstration Zero-Hour Test Results, Engine B								
Engine	Test Cycle	Fuel	HC	CO	NOx	NOx+HC	BSFC	Comments
B	-C2	LPG	0.94	7.37	11.7	12.64	0.526	Baseline emission levels (uncontrolled, see Table 2)
B	-C2	LPG	0.09	2.1	0.01	0.10	0.558	Closed-loop, automotive TWC, 4 hours degreen time
		% reduction	90.4	71.5	99.9	99.2	-6.08	

Note that the impressive percentage reductions shown here for NOx and HCs equal or exceed those presented in Table 5 (which were based on the average of a brief survey of previous test results.) While the CO percentage reduction is somewhat less than that presented in Table 5, reductions of all three pollutants are still quite impressive for an off-the-shelf system. However, one must keep in mind that this is for a fresh engine and catalyst, and it remains to be seen how aging will affect the emission control system performance.

Unfortunately, the fuel consumption of the engine showed a moderate increase, as shown by the BSFC numbers in Table 6. This effect was expected for a comparison made to a new LPG engine with factory calibration. However, as discussed previously, it is expected that the modified engine would show fuel economy benefits if compared to an in-use engine whose mixture ratio has been tampered with or has deteriorated over time.

2. Engine B Deterioration Factor Test Results

This engine is currently being installed in an operating forklift at SwRI's facilities for operating time accumulation. Upon accumulation of 250 hours of operation, it will be removed and retested for emissions performance deterioration in the near future.

3. Engine E Zero-hour Test Results

Engine E was chosen from the gasoline engines listed in Table 2 as being a worst case engine in terms of emissions. It is an air-cooled, side valve engine, calibrated by the manufacturer to run rich under all conditions for combustion temperature control purposes. The rationale for selecting this engine for modification and testing is that if it can be equipped to meet the proposed standards, then it should be possible to improve the emissions from almost any LSI engine.

SwRI has equipped this engine with several pieces of equipment for reducing its emissions. They chose the Total

Engine Control (TEC) fuel control system provided by Electromotive Corporation, which has both open- and closed-looped fuel control capabilities as well as ignition system control capability. The TEC controller drives an off-the-shelf automotive throttle body injector system. A dual-bed catalyst approach is used. The first catalyst carries out the NOx reduction reactions and the second catalyst conducts HC and CO oxidation. An engine driven air pump injects air into the exhaust flow between the two converters to supply the oxidation reactions.

SwRI has calibrated the control system to supply a stoichiometric mixture ratio, under closed-loop control, at low and medium load conditions. The system operates open-loop, and is calibrated to supply a rich mixture, under high load conditions to avoid cylinder head maximum temperature constraints (the cylinder head temperature is an indicator of when the fuel-air mixture burns sufficiently cool to avoid engine damage). Table 7 presents the zero-hour emission test results.

Table 7 - TWC Demonstration Zero-Hour Test Results, Engine E

Engine	Test Cycle	Fuel	HC	CO	NOx	NOx+HC	BSFC	Comments
B	-D2	gasoline	10.7	479	1.70	12.4	1.10	Baseline emission levels (uncontrolled, see Table 2)
B	-D2	gasoline	0.25	26	1.83	2.08	0.927	Closed-loop, catalyst
		% reduction	97.7	94.6	-7.6	83.2	15.7	

These data show that the modifications made to this engine are capable of providing significant emission reductions. Because this engine runs very rich in its baseline configuration, it is not surprising that the modified configuration, with its emphasis on stoichiometric operation, shows a moderate increase in NOx levels. However, the combined NOx+NMHC levels are well below the level of the proposed standard, demonstrating the feasibility of meeting the proposed standard with even the least clean of current engines. An added benefit is the major improvement in fuel consumption, which could go far towards offsetting the cost of the control components.

4. Engine E Deterioration Factor Test Results

This engine, including the emission control equipment described above, will presently be installed in an irrigation water pump for operating time accumulation. Upon accrual of 250 hours of operation, it will be removed and retested for emissions performance deterioration.

IV. Summary and Conclusions

The large spark-ignition engine category contains a wide array of engine types, fuels, configurations and applications. LSI engines can: be single- or multi-cylinder; operate on LPG, CNG or gasoline; be air-cooled or water-cooled; range from 25 horsepower to several hundred; be used in high load/steady speed applications like generator sets, or variable speed and load vehicular equipment like forklifts; be of modern overhead valve design or older side valve configuration; and so forth. Because of this large variety, one might expect that many different approaches would be needed to reduce their emissions. However, ARB staff have considered the technologies available and also consulted with an experienced contractor for its opinion on the best way to reduce LSI engine emissions, and to what level these emissions can be practically reduced. As a result, staff has concluded that, in most cases, the use of electronic engine controls and catalytic converters, properly applied and engineered, can be made to reduce LSI engine emissions sufficiently to meet the proposed standards.

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